LUNAR IMPACT GLASSES: WHAT ARE THEY TELLING US? N. E. B. Zellner[1], J. W. Delano[2], T. D. Swindle[3], D. C. B. Whittet[4], [1]Department of Physics, 611 E. Porter St. Albion College, Albion, MI 49224, USA (nzellner@albion.edu), [2]University at Albany (SUNY), Albany, NY 12222 (jdelano@atmos.albany.edu), [3]University of Arizona, Tucson, AZ 85721 (tswindle@U.Arizona.Edu), [4]New York Center for Astrobiology and Rensselaer Polytechnic Institute, Troy, NY 12180 (whittd@rpi.edu).

Introduction: Understanding the time-varying impact flux in the Earth-Moon system allows us to determine the occurrence of impact events whose markers are no longer visible on Earth. If we know what the impact flux looked like, we can begin to speculate about when conditions became favorable for sustainable life on Earth. Since they are so close together in space, the Moon serves as a good proxy for understanding impact events on Earth, but the timing of impacts on the Moon over the last 4.5 billion years (Ga) is not well understood.

Lunar impact glasses offer the potential for providing compositional information about local and remote areas of the Moon [1, 2, 3] and may also place constraints on the impact history in the Earth-Moon system. We have studied ~2500 lunar impact glasses from the Apollo 14, 16, and 17 landing sites and obtained $^{40}Ar/^{39}Ar$ ages on a subset of them in order to better understand the global lunar impact flux and how it might be applied to Earth. These impact glasses have a wide compositional range indicating their local, regional, and global provenance. This information is important for interpreting isotopic ages of individual impact glasses.

Previous Studies: Previous investigators have reported $^{40}Ar/^{39}Ar$ ages on lunar samples such as rock fragments [e.g., 4, 5] and melt clasts in meteorites [e.g., 6] in order to provide evidence as to whether or not a lunar cataclysm occurred ~3.9 Ga. These samples represent a wide variety of terrains, and so far, there is no convincing evidence in the lunar melt rock record for basin-forming impacts significantly older than 3.9 Ga. Others have looked at lunar samples (e.g., rock fragments [e.g., 7] and lunar impact glasses [e.g., 8]) from one landing site and estimated the lunar impact flux at that location. However, since the samples were collected at one site, a reliable interpretation of the global lunar impact flux cannot be made.

Our Results: Of the 92 glasses dated so far using the $^{40}Ar/^{39}Ar$ method, reliable ages (plateaus with steps that agree and yield small uncertainties) for 65 impact glasses have been obtained (Figure 1).

Ages: Samples with ages >4000 Ma are rare, as is true for Apollo impact rocks [4], impact melts from lunar meteorites [6], and other lunar impact glass data sets [e.g., 8]. In fact, none of our Ar/Ar ages of lunar impact glasses plotted in Figure 1 exceed 3.9 Ga. Additionally, few show ages consistent with a recent (last ~500 Ma) increase in the impact flux, as reported in [8].

Four impact glasses from the Apollo 16 landing site were all found to yield a likely age of ~3.73 ± 0.04 Ga and, based on petrography and chemical compositions, were determined to have formed in one impact event and not four [3]. Additionally, an Apollo 17 sample, with a different geochemical composition, shows an age of 3.74 ± 0.05 Ga. These ages are close to the accepted age for the Imbrium Basin [3.84-3.85 Ga; 5] and even closer to the age of 3.77 Ga argued by [9]. A second Apollo 17 sample shows an age of 3580 ± 45 Ma and falls at the end of the Late Heavy Bombardment or just after the primary Lunar Cataclysm, if it occurred.

Nine impact glasses from the Apollo 14, 16, and 17 landing sites show formation ages of ~800 Ma [10]. Intriguingly, these nine impact glasses have just seven different compositions, implying seven different impact events in the same timeframe. These glasses are similar in age to some Apollo 12 rock fragments [7] and a few Apollo 12 impact glasses [8]. Combining these data sets, we can begin to infer a possible global lunar bombardment since these four landing sites are separated by several hundred kilometers.

Shapes: The chemical compositions of ~1200 glass fragments and glass spherules from the Apollo 16 landing site have been compared [3]. While impact glasses with chemical compositions similar to local materials (i.e., Apollo 16 rocks and regoliths) are abundant, glasses with exotic compositions (i.e., transported from other areas of the Moon) account for up to ~30% of the population. Additionally, ~40% of glass *fragments* have compositions that are exotic to the Apollo 16 region, while only ~10% of glass *spherules* have exotic compositions. From this, we infer that glass fragments are more frequently the product of large and distant impact events, in which these glasses have been transported and broken during transport. Specifically, the original glasses may have been in the form of spherical melt blobs that were centimeter-or-greater in size that then shattered into smaller fragments upon landing. In contrast, locally produced glasses (*spherules* having chemical compositions similar to local materials) may have been formed by smaller cratering events that generated smaller quantities of impact melt droplets that landed on the nearby surface at modest speeds without shattering.

Similar studies that compare shape and compositions with age have been undertaken for the Apollo 14 [11] and Apollo 17 [12] lunar impact glasses whose ages have been determined. Though much smaller data sets, similar trends are seen, in which glasses with exotic compositions are more likely to be fragmented. More data are needed to verify the trends in general.

Conclusion: Lunar impact glasses from the Apollo 14, 16, and 17 landing sites show a wide range of ages and compositions, and there is evidence of a correlation between shape and provenance of origin.

By integrating geochemistry and age [3], multiple impact samples formed at the same time in the same terrain can be removed from the data set so that the impact flux, whether local or global, is not artificially inflated. The challenge comes in trying to distinguish among the impact events, including determining which samples (impact glasses, melt rock, meteorites) were formed during the same impact event and which samples were formed in unrelated impact events.

Interpreting these compositions, along with the ages, will help us continue to understand the impact processing of the lunar surface and the bombardment history in the Earth-Moon system so that we can address important issues, including the form of the impact distribution with respect to time (e.g., smooth decline versus cataclysmic spike), whether there is periodicity in Earth-Moon cratering history, and the applicability of the lunar record to other planets. Of particular interest to astrobiology and the study of the origin of life is determining the impact flux prior to ~3.7 Ga ago, and specifically, whether or not early life, if it existed on Earth before 4 Ga ago, may have been destroyed [e.g., 13, 14] during these early impact events.

Work in progress: We are currently evaluating the diffusivity of Ar in natural and synthetic lunar glasses (for a wide range of chemical compositions) to evaluate the retentivity of radiogenic Ar over billions of years in the lunar thermal regime. These experiments will determine if the ages of lunar impact glasses are susceptible to Ar loss (i.e., loss of isotopic age memory) during lunar processes. Since lunar impact glasses are abundant in the regolith samples returned during the six Apollo missions, and remain under-utilized even to this day, they represent a potentially valuable source of information bearing on the time-dependent impact flux in the Earth-Moon system.

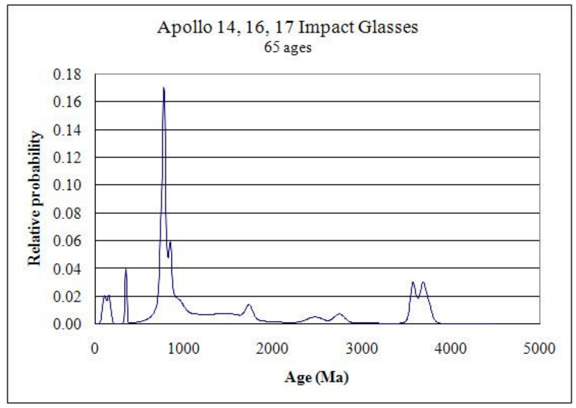

Figure 1. Ideogram of lunar impact glass ages as seen in [10]. Each age is represented by a Gaussian distribution of unit area; precisely determined ages appear as tall spikes and poorly determined ages appear as low, broad humps.

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